

# Cover crops effect on farm benefits and nitrate leaching: Linking economic and environmental analysis

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## A B S T R A C T

Introducing cover crops (CC) interspersed with intensively fertilized crops in rotation has the potential to reduce nitrate leaching. This paper evaluates various strategies involving CC between maize and compares the economic and environmental results with respect to a typical maize–fallow rotation. The comparison is performed through stochastic (Monte-Carlo) simulation models of farms' profits using probability distribution functions (pdfs) of yield and N fertilizer saving fitted with data collected from various field trials and pdfs of crop prices and the cost of fertilizer fitted from statistical sources. Stochastic dominance relationships are obtained to rank the most profitable strategies from a farm financial perspective. A two-criterion comparison scheme is proposed to rank alternative strategies based on farm profit and nitrate leaching levels, taking the baseline scenario as the maize–fallow rotation. The results show that when CC biomass is sold as forage instead of keeping it in the soil, greater profit and less leaching of nitrates are achieved than in the baseline scenario. While the fertilizer saving will be lower if CC is sold than if it is kept in the soil, the revenue obtained from the sale of the CC compensates for the reduced fertilizer savings. The results show that CC would perhaps provide a double dividend of greater profit and reduced nitrate leaching in intensive irrigated cropping systems in Mediterranean regions.

### Keywords:

Fallow  
Economic analysis  
Risk analysis  
Maize  
Monte-Carlo simulation  
Water quality

## 1. Introduction

There are very few studies that combine economic and environmental approaches to analyse the adoption of agricultural techniques using experimental data and actual economic evaluations at farm level. Nowak (1992) claims that farmers fail to adopt new technologies because they are either unwilling or unable, although adoption reluctance is frequently rooted in low economic profitability or poor knowledge. Economic analyses permit a comparison between the profit that farmers obtain from agricultural products and the cost of adopting specific agricultural techniques. Environmental studies are complex, and evaluating the indicators that are representative of the environmental impact of an agricultural system is a complex task that is conducted by specialized groups and methodologies. Multidisciplinary studies might help to develop reliable approaches that would contribute to choosing the best agricultural strategies based on linking economic and environmental benefits.

Cover cropping was chosen for this study because, despite the evident environmental services provided and the range of agroeconomic benefits documented in the literature, farmers' adoption of the technique is still limited (Thorup-Kristensen et al., 2003). Growing cover crops (CC) could lead to extra costs for the farm in three different forms: direct, indirect, and opportunity costs (Snapp et al., 2005). Direct CC costs include the cost of establishment, seed, killing, and harvesting, but in some cases they replace other costs such as costs of tillage or herbicide applied when fallow. This means that only incremental costs should be considered. The indirect component is associated with hindering the establishment of the succeeding cash crop by slow soil warming, water depletion, or delayed organic N release. Other indirect costs are associated with factors that reduce expected benefits such as weather conditions, over-vigorous CC, or hard-to-kill CC acting as weeds. Lastly, the forgone benefits of producing another cash crop, a clear opportunity cost, during CC time could perhaps be the greatest cost. However, in most regions, CC are usually grown, replacing fallow between two cash crops, when time or environmental limitations do not allow for planting another profitable cash crop, so the choice is between fallow and CC. Differences in climatic conditions generate a great variability in CC growth, which, combined with price volatility, increases the variability of

farmers' incomes. Risk analyses of economic scenarios based on probability distributions might help to compare the different alternatives.

Excess nitrates in water bodies causing non-point pollution are one of the major environmental problems related to agricultural systems. Meeting the ambitious goal of reducing nitrate pollution in the entire EU would entail reducing the welfare of the farm sector by 25% (Oenema et al., 2009). However, at farm level some studies suggest that potential improvements could be made to recommendations regarding N fertilizer (Deen, 2007). In Spain, Kahil and Albiac (2011) identified strategies to reduce emissions in agriculture, estimating a cost of 2 € per kilogram of reduction in N leaching. Mikkelsen et al. (2009) obtained the same cost for Denmark, whereas Hoogeveen et al. (2008) obtained a range of 3–8 € per kg of reduced N leaching for The Netherlands, and in the evaluation of Oenema et al. (2009) the figure was 4 €. Particularly, irrigated agriculture contributes to crops' productivity and diversification but has a large potential for nitrate contamination of groundwater (Vázquez et al., 2006). Replacing intercrop fallow with CC has been reported to reduce  $\text{NO}_3^-$  leaching in irrigated agriculture by increasing the retention of post-harvest surplus inorganic N and improving the efficiency of N use (Salmerón et al., 2011; Gabriel et al., 2012). The challenge is to identify CC management strategies that could reduce nitrate leaching in irrigated systems and increase, or at least not impair, farm profits, without government aids.

The goal of this paper was to evaluate the economic impact of replacing the usual winter fallow with CC in irrigated systems using stochastic Monte-Carlo simulations of key farms' financial performance indicators. In an attempt to relate economic and environmental criteria, the nitrate leaching was plotted versus the economic benefit for the scenarios where data were available. Strategies are thus judged on their joint effects on the farm economy and the nitrate leaching reduction.

## 2. Materials and methods

### 2.1. Soil and site characteristics

The field studies were conducted from October 2006 to April 2011 at La Chimenea Field Station (40°03'N, 03°31'W, 550 m a.s.l.) in Aranjuez (Madrid, Spain). Located in the central Tagus river basin, this site has a Mediterranean semiarid climate (Papadakis, 1966). Rainfall is 347 mm per year, with a dry period including June to September, and it is therefore classified as *Thermomediterranean* (UNESCO, 1979). The soil at the field site is a silty clay loam *Typic Calcixercept* (Soil Survey Staff, 2003), which is alkaline and rich in organic matter and carbonates and contains a low stone content throughout the soil profile.

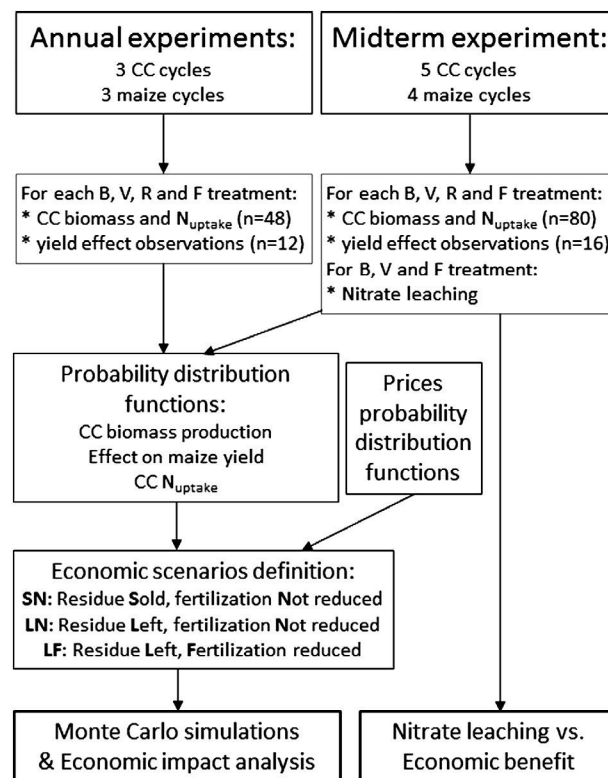
Observed data employed for the analysis were obtained from various experiments conducted in the same field station. The first experiment lasted from October 2006 to April 2011, and it will be referred to in the article as the 'midterm experiment'. In this trial a CC–maize rotation was repeated in the same plot during five CC periods and four maize crops to study the cumulative effect. The other three 'annual experiments', where maize was grown after fallow or various CC, were carried out in different fields separated by ~100 m each year (from October 2006 to October 2009). All experiments follow the same factorial design, with CC as the main factor. At the beginning of a trial, each field (3000 m<sup>2</sup>) was split at random into sixteen plots (144 m<sup>2</sup>), leaving borders to prevent side effects, and distributed in four replications for each of four treatments: barley (*Hordeum vulgare* L., cv. Vanessa), vetch (*Vicia villosa* L., cv. Vereda), rapeseed (*Brassica napus* L., cv. Licapo), and fallow. CC were sown in early October and killed in late winter (March),

allowing maize seeding of the entire trial area three weeks later (early April) and harvesting in early October. The fields were left fallow for a minimum of 2 years, and had not received organic amendments or N fertilizer during four years prior to the beginning of the trial.

### 2.2. Cover crop biomass production and N uptake

Biomass production was measured in each plot and year of mid-term and annual experiments ( $n = 128$ ; Fig. 1). Four 0.5 m × 0.5 m squares were randomly harvested from each plot before killing the CC by applying glyphosate. Aerial biomass was cut by hand at soil level, dried, weighed, and ground. Subsamples of the dry material were analysed for N concentration by Dumas combustion method with a LECO FP-428 analyser (Leco, St. Joseph, MO, US), and N content in each plot was calculated as the product of biomass and N concentration.

The software @RISK (PALISADE, 2007) was used for constructing the histogram and fitting the best probability distribution function (pdf) for each CC biomass data set (Fig. 1). This software allowed a value sequence to be fitted to a pdf, giving its moments and characterization. Fifteen different models were fitted and the best was selected based on the  $\chi^2$  criterion. A truncation at 0 kg ha<sup>-1</sup>, as the absolute minimum biomass, was imposed in the fitting of the pdf. The function was truncated too, as the maximum for these crops and conditions, at the maximum biomass observed in a simple square during the different years for each CC. The same procedure was used for constructing the histogram and fitting the best pdf to the set of CC N uptake data (Fig. 1). The functions were truncated again at 0 kg N ha<sup>-1</sup>, as the absolute minimum N uptake, and at the maximum N uptake observed in a simple square during the different years for each CC for the fitting of the pdf.



**Fig. 1.** Diagram of field data processing for both economic impact and economic-environmental analysis. Treatment considered were three cover crops (CC; barley (B), vetch (V) and rapeseed (R)) and fallow (F) as different land use between two following maize crops.



### 2.3. Effect of cover crop on maize yield

Maize yield was measured in each plot by harvesting two 10 m central rows with an experimental harvester to minimize the yield heterogeneity inside the plot (four measurements per treatment and per year). The effect on maize yield was calculated for each CC plot as the difference between the plot yield and the mean yield in the fallow treatment of the corresponding experiment ( $n = 28$  for each CC treatment; Fig. 1). The software @RISK (PALISADE, 2007) was used for constructing the histogram and fitting the best probability distribution to the set of CC effects on crop yield, using the same procedure as described above in Section 2.2.

### 2.4. Fertilizer saving due to cover crops

Soil mineral N content ( $N_{\min}$ ) was determined in the midterm experiment plots before planting maize and after harvesting (Gabriel and Quemada, 2011).  $N_{\min}$  was obtained from four soil cores to 1.2 m depth at 0.2 m intervals taken from each plot. Soil samples were extracted with 1 M KCl, centrifuged, and decanted, and a subsample of the supernatant volume was saved for analysis. Nitrate concentration in the extracts was determined by spectrophotometry (Keeney and Nelson, 1982), and ammonium was measured using the method of Solorzano (1969). All treatments and experiments were fertilized during the maize period in the same way with 210 kg N ha<sup>-1</sup> as ammonium nitrate each year. N surplus was obtained for each plot as the difference in  $N_{\min}$  in the soil profile after harvesting the maize and before planting. The fraction of N in the CC biomass available for the next maize crop ( $N_f$ ) was calculated for each plot as the difference between the plot's N surplus and the mean N surplus in the fallow treatment for each year and experiment, divided by the total N uptake in the precedent CC. Fertilizer saving due to a CC was obtained by multiplying the pdf of the CC N uptake by  $N_f$ .

### 2.5. Economic analysis

The baseline scenario in the economic analysis was the fallow followed by a maize crop. When introducing a CC to replace the fallow, two management options were considered: (1) leaving the CC residues in the soil as a green manure (L) or selling the CC biomass for animal feeding (S); (2) reducing the N fertilizer application based on the potential saving derived from CC residues (F) or not (N). By combining these management practices, three alternative scenarios were proposed (Fig. 1): (i) CC residue remained in the field but there was no fertilizer reduction (LN); (ii) CC residue remained in the field as green manure and N fertilizer was reduced (LF); and (iii) CC biomass was sold and there was no fertilizer reduction (SN).

Stochastic net benefits (€ ha<sup>-1</sup>) of each option are defined as follows:

$$\tilde{\pi}_{LN} = \tilde{Y} \times \tilde{P}_m - C_L \quad (1)$$

$$\tilde{\pi}_{LF} = \tilde{Y} \times \tilde{P}_m + [(N_{cc} \times N_f \times \tilde{P}_f)/N_{fc}] - C_L \quad (2)$$

$$\tilde{\pi}_{SN} = \tilde{Y} \times \tilde{P}_m + \tilde{B}_{cc} \times \tilde{P}_b - C_S \quad (3)$$

where  $\tilde{Y}$  was the stochastic yield variation (Mg ha<sup>-1</sup>);  $\tilde{P}_m$  was the stochastic maize price (€ Mg<sup>-1</sup>);  $\tilde{N}_{cc}$  was the stochastic N uptake by CC (kg N ha<sup>-1</sup>);  $N_f$  was the fraction of N in the CC biomass available for the next maize crop;  $\tilde{P}_f$  was the stochastic fertilizer price (€ kg<sup>-1</sup>);  $N_{fc}$  was the N concentration of the fertilizer;  $\tilde{B}_{cc}$  was the stochastic biomass produced by CC (Mg ha<sup>-1</sup>);  $\tilde{P}_b$  was the stochastic CC biomass price as forage (€ Mg<sup>-1</sup>); and  $C$  was the extra cost of CC (€ ha<sup>-1</sup>) and was calculated as the cost of the activities not required for fallow (Table 1), where  $C_L$  was the cost when residues were left without being lifted and  $C_S$  the cost when residues were lifted and sold. Variable costs accounted for were CC seed, contact herbicide (applied only when the residue was lifted and not sold), and fuel (gasoil). The extra fuel consumption was related to sowing with a centrifugal spreader, shallow tillage with seedbed finisher for seed covering, and herbicide duster application for killing the CC when residues remain in the field. When CC biomass was sold and extra gasoil consumption was considered for lifting straw operations. Equipment expenses were not considered, because the operations required the usual farm machinery (centrifugal spreader, seedbed finisher, herbicide duster, and straw lifting equipment). Extra labour costs were not considered because the operations involved are fast (0.5 h ha<sup>-1</sup> for the centrifugal spreader, 2 h ha<sup>-1</sup> for tillage, 1 h ha<sup>-1</sup> for herbicide dusting, and 4 h ha<sup>-1</sup> extra for lifting) and are usually included in workers' wages or family farm labour with no opportunity cost.

Forage, maize, and fertilizer prices were obtained monthly from the market (MAAMA, 2012) and pdfs were obtained as in Rey et al. (2011) as the real revenue that a farmer received or paid. Monthly CC forage prices were based on monthly observed alfalfa prices, corrected by a coefficient for each CC forage, obtained by annual comparison of observed data for alfalfa and the CC forage from 1985 to 2009 (MAAMA, 2012). The software @RISK (PALISADE, 2007) was used for constructing the histogram and fitting the best probability distribution to the set of prices, with monthly observed data from February 2005 to December 2011 for vegetal products and from January 2005 to September 2011 for fertilizer, using the same procedure as described above.

Monte-Carlo simulations were applied to CC biomass, CC N uptake, prices (maize, CC biomass, and fertilizer), and yield variation probability distributions, using models (1), (2), and (3). Economic fertilizer savings were calculated considering the  $N_f$  for each CC and the stochastic fertilizer price for ammonium nitrate (33.5% N).

### 2.6. Effect of cover crop on nitrate leaching and economic benefit

A second analysis was done comparing observed economic impact of introduction of a cover crop and measured nitrate leaching variations produced. Nitrate leaching data used in this work were obtained from Gabriel et al. (2012) and CC biomass production and yield variation for the economic benefit analysis from Gabriel and Quemada (2011) in the same experimental field. The data were collected in the midterm experiment and were available for three treatments (vetch, barley, and fallow; Fig. 1) and four replications during 4 years (2007–2010). In this case, nitrate leaching data were available for observed economic alternatives SN (CC biomass sold and no fertilizer reduction) and LN (CC residue incorporated in the soil and no fertilizer reduction).

**Table 1**  
Cost items used for economic analysis. Tillage operations' costs involved gasoil cost.

	Seed (€ Mg <sup>-1</sup> )		Sown € ha <sup>-1</sup>	Tillage	Herbicide	Lift	Cost without lift (€ ha <sup>-1</sup> )	Cost with lift (€ ha <sup>-1</sup> )
Vetch	51.00	7.65	1.00	5.00	3.00	18.00	71.65	31.65
Barley	21.70	3.91	1.00	5.00	3.00	18.00	67.91	27.91
Rapeseed	1450	8.70	1.00	5.00	3.00	18.00	72.70	32.70

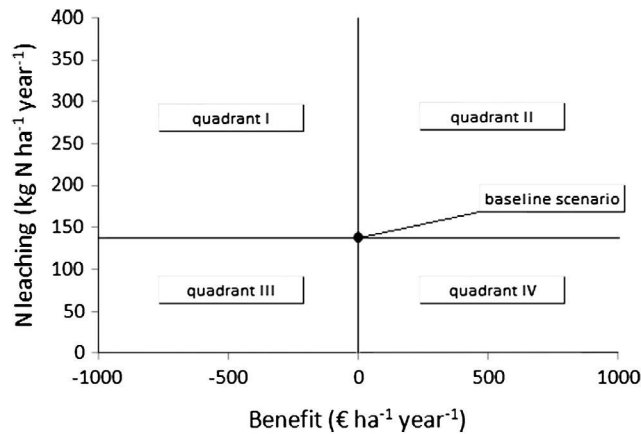


Fig. 2. Comparison framework for the baseline scenarios and the alternatives.

To relate economic and environmental criterions, the total nitrate leaching accumulated for each CC/maize cycle was plotted versus the economic benefit of the baseline and alternative scenarios. Two lines providing the values pertaining to the baseline scenario divided the plot into four quadrants. These quadrants represented four areas where the viability of the alternatives was different with respect to the baseline scenario (Fig. 2). In the

upper-left area, the alternatives increased nitrate leaching and decreased the economic benefit (quadrant I). In the lower-right area (quadrant IV), the alternatives were better in environmental and economic terms than the baseline scenario; that is, the nitrate leaching was reduced and the economic benefit increased. In quadrant III both nitrate leaching and the economic benefit decreased, while in quadrant II both increased. In quadrant III, the alternatives would be feasible if subsidies to compensate for the economic losses were offered to the growers. In quadrant II the profit obtained is associated with an increase of the environmental impact. In order to observe the economic sustainability under different economic scenarios, possible economic benefits when forage and maize grain prices were either increase or decrease by 33% were also studied.

### 3. Results

#### 3.1. Cover crop biomass production

The pdf adjusted to the CC biomass production observed in all the experiments that presented the best  $\chi^2$  was the log-logistic with the minimum at zero (Fig. 3) with a  $\chi^2$  value at least one point smaller on average than the second-best fitted distribution. The log-logistic distribution is the probability distribution of a random variable whose logarithm has a logistic distribution. It is similar in

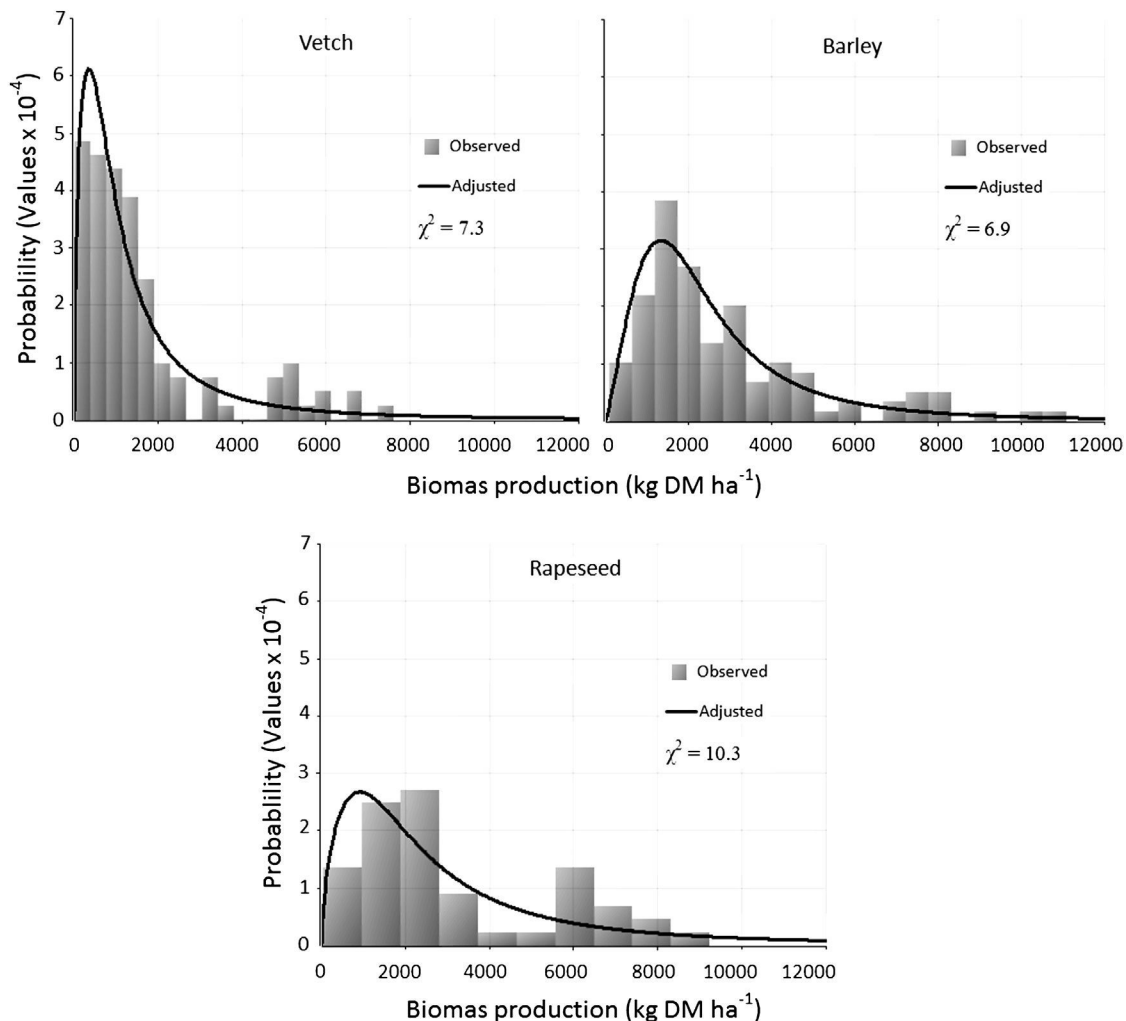


Fig. 3. Log-logistic probability distributions adjusted to observed cover crop biomass production.



shape to the log-normal distribution but has heavier tails. Following the log-logistic distribution, the biomass production mode (i.e. the most probable production) was 1328 kg ha<sup>-1</sup> for barley, 348 kg ha<sup>-1</sup> for vetch, and 907 kg ha<sup>-1</sup> for rapeseed. Mean biomass production was 3147 kg ha<sup>-1</sup> for barley, being larger than 2132 kg ha<sup>-1</sup> in 50% of years; 2351 kg ha<sup>-1</sup> for vetch, being larger than 993 kg ha<sup>-1</sup> in 50% of years; and 4856 kg ha<sup>-1</sup> for rapeseed, being larger than 2277 kg ha<sup>-1</sup> in 50% of years. Biomass distribution in the case of rapeseed only was fitted for 60% of years, because in the other 40% it corresponded to years with 0 kg ha<sup>-1</sup>, when the rapeseed did not succeed in becoming established. Therefore, we modeled this combining a binomial distribution (1, 0.6) with a log-logistic. Since the log-logistic is not bounded in the right tail we truncated it at the following values, 11,084, 9245, and 7605 kg ha<sup>-1</sup> for barley, rapeseed, and vetch, respectively, which are considered extremes yield values for the study sites.

### 3.2. Effect of cover crop on maize yield

The pdf adjusted to the effect on crop yield observed in all the experiments that presented the best  $\chi^2$  was the triangular distribution without restrictions (Fig. 4). That distribution is widely used in risk analysis because of its intuitive nature and speed of use (Hardaker et al., 1997). Following the triangular distribution, the mode effect on maize yield was an increase of 1537 kg ha<sup>-1</sup> when fallow was replaced by vetch, an increase of 1183 kg ha<sup>-1</sup> when it was replaced by barley, and a decrease of 1474 kg ha<sup>-1</sup> when it was replaced by rapeseed. The mean effects for vetch and barley were increases in maize yield of 869 and 334 kg ha<sup>-1</sup>, respectively,

while the mean effect for rapeseed was a decrease in maize yield of 221 kg ha<sup>-1</sup>.

### 3.3. Fertilizer saving due to cover crops

Fertilizer saving was obtained by multiplying the pdf of the CC N uptake by  $N_f$ . The best  $\chi^2$  pdf adjusted to the CC N uptake was the log-logistic with the minimum at zero (Fig. 5). Following this distribution, the CC N uptake mode was 21.8 kg N ha<sup>-1</sup> for barley, 12.1 kg N ha<sup>-1</sup> for vetch, and 32.3 kg N ha<sup>-1</sup> for rapeseed. Mean N uptake was 63.8 kg N ha<sup>-1</sup> for barley, being larger than 39.3 kg N ha<sup>-1</sup> in 50% of years; 82.0 kg N ha<sup>-1</sup> for vetch, being larger than 34.5 kg N ha<sup>-1</sup> in 50% of years; and 122.1 kg N ha<sup>-1</sup> for rapeseed, being larger than 67.0 kg N ha<sup>-1</sup> in 50% of years. Similarly to the rapeseed yield, N uptake distribution was modeled combining the binomial (1, 0.6) and log-logistic to account for the fact that in 40% of the years the crop did not become established successfully. The log-logistic pdfs were truncated in the right with values 274.3, 286.6, and 243.2 kg N ha<sup>-1</sup> for barley, rapeseed, and vetch, respectively, in order to avoid impossible values in the Monte-Carlo simulations. The average  $N_f$  obtained were 0.90 for barley, 0.81 for vetch, and 0.65 for rapeseed.

### 3.4. Economic impact

Introducing a CC involved extra expense in comparison with fallow (Table 1). The extra cost of CC was 67.91 € ha<sup>-1</sup> for barley, 72.70 € ha<sup>-1</sup> for rapeseed, and 71.65 € ha<sup>-1</sup> for vetch when the residues were left in the field. When CC biomass was lifted and sold as animal feeding the extra cost of CC was reduced to 27.91 € ha<sup>-1</sup> for barley, 32.70 € ha<sup>-1</sup> for rapeseed, and 31.63 € ha<sup>-1</sup> for vetch. The

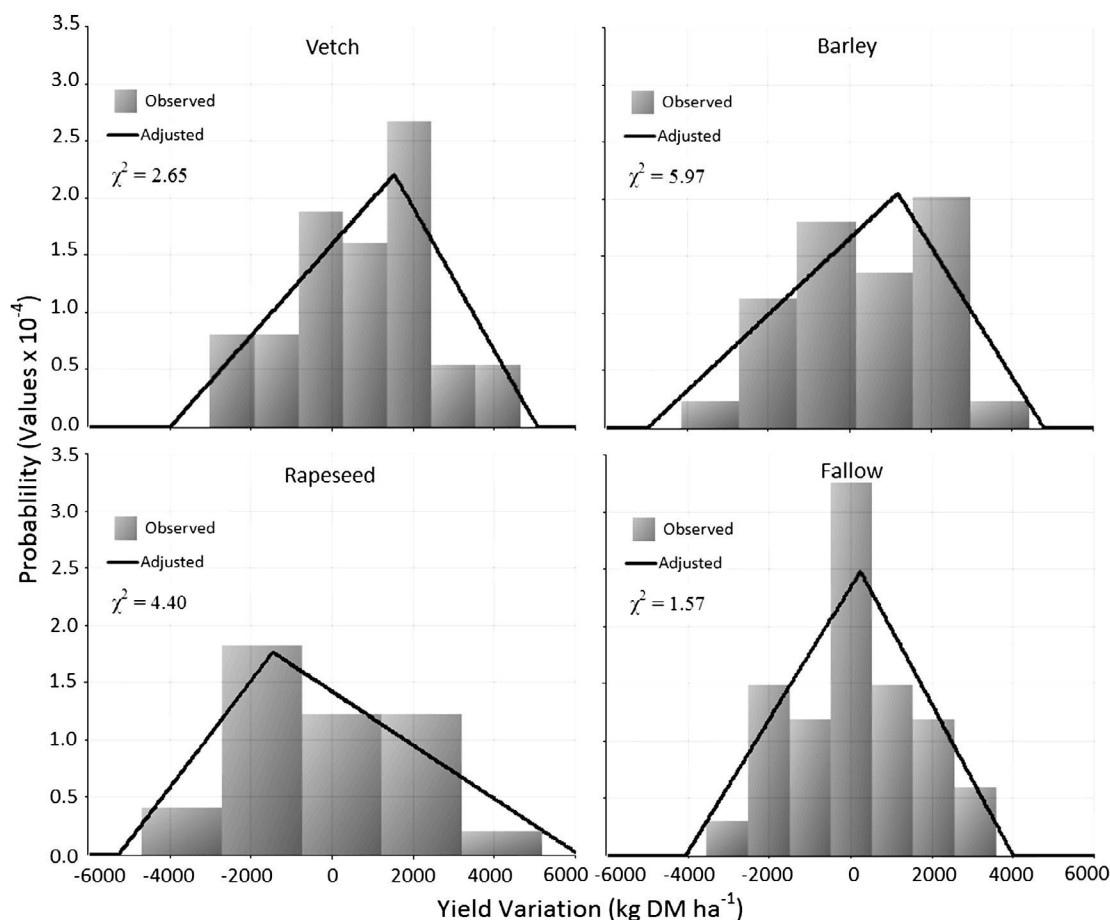


Fig. 4. Probability distributions of the cover crop effect on maize yield.

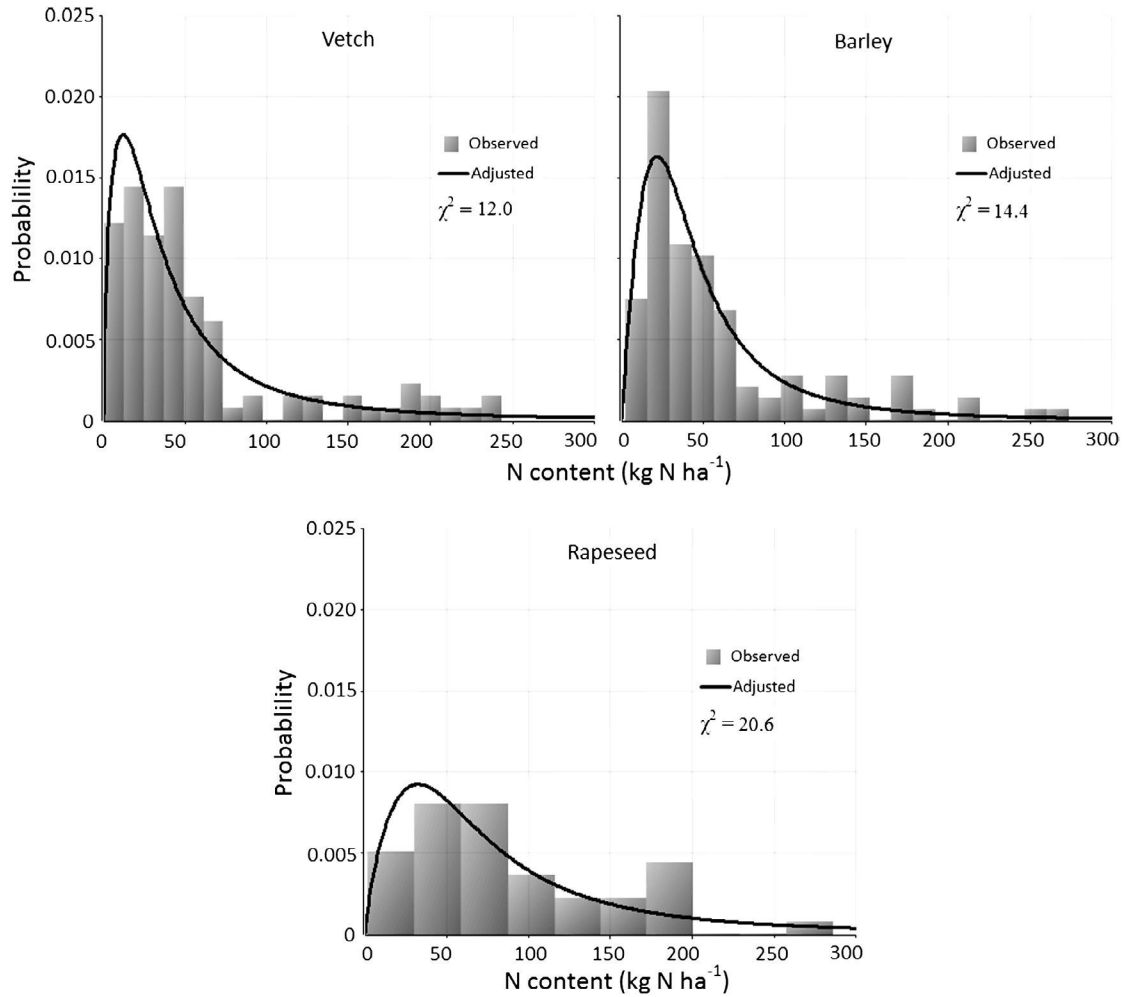


Fig. 5. Cover crop N content probability distribution.

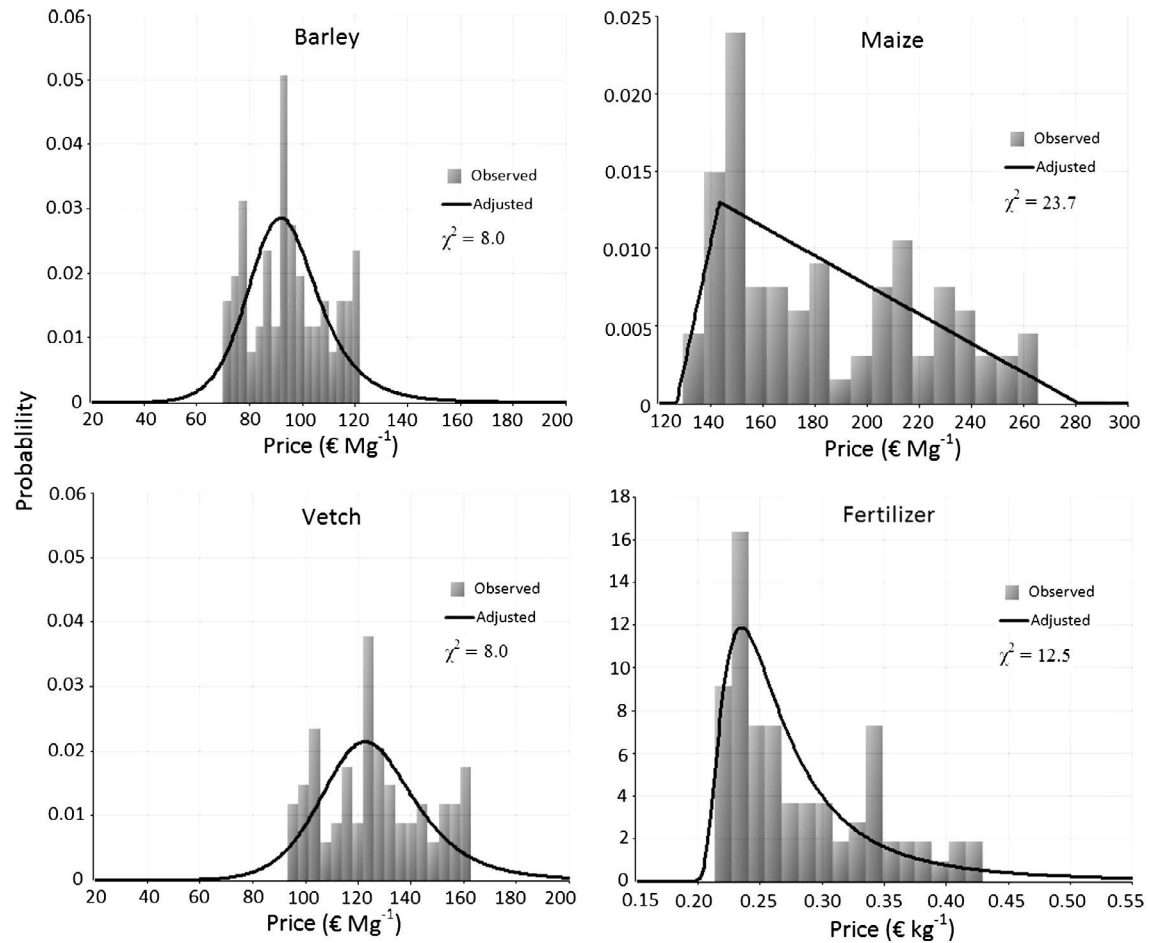
main difference came from the variable costs, which were 64.00 € ha<sup>-1</sup> if the CC residue was left in the field or 24.00 € ha<sup>-1</sup> if it was collected for selling. This amount was broken down into the cost of the contact herbicide, which was 55 € ha<sup>-1</sup>, and the gasoil cost, which varied depending on the use of the CC biomass. Seed cost increased the variable costs by 3.91 € ha<sup>-1</sup> for barley, 7.65 € ha<sup>-1</sup> for vetch, and 8.70 € ha<sup>-1</sup> for rapeseed.

The pdfs for forage, maize, and fertilizer prices were fitted to the best  $\chi^2$  distribution for the monthly data observed (Fig. 6). Maize price was adjusted to a triangular pdf with a mean of 183.52 € Mg<sup>-1</sup>. This price took into account 14% humidity in the grain. Forage prices were adjusted to log-logistic functions with means of 71.72 € Mg<sup>-1</sup> for barley and rapeseed (33.3% lower than the alfalfa hay price) and 125.56 € Mg<sup>-1</sup> for vetch (11.8% lower than the alfalfa hay price). These prices considered a forage humidity of 12%. When the model was applied, a 0.35 correlation between forage and maize grain prices observed in the data was applied. The fertilizer price fitted a Pearson5 with mean at 0.286 € kg<sup>-1</sup> of ammonium nitrate (33.5% N). In this case, the correlations observed and applied to the model were 0.40 with the maize price and 0.59 with the forages.

The biomass produced by CC was not correlated in any of the three CC with successive maize yield variation, with the Pearson's  $r$  ranging from 0.098 for rapeseed treatment to -0.312 for barley. Based on this, the economic analysis of CC was conducted considering maize yield variation and CC biomass production probabilities as independent variables for the three scenarios defined. Monte-Carlo simulations (each with 10,000 iterations) were per-

formed for models (1), (2) and (3), using the fitted probability distributions of yields, multiplied by the corresponding pdfs of prices and subtracted corresponding costs for benefit estimation. In the LN scenario, where residues were not sold and there was no fertilizer reduction, vetch increased net benefits to 115 € ha<sup>-1</sup> on average and barley increased them to 4 € ha<sup>-1</sup>, due to an increase in maize yield, while rapeseed decreased the net benefits to 118 € ha<sup>-1</sup> (Table 2). However, when residue was sold, the benefits increased to 356 € ha<sup>-1</sup> on average for the vetch, 256 € ha<sup>-1</sup> for barley, and 49 € ha<sup>-1</sup> for rapeseed. An intermediate situation was presented when residue was not sold but was considered a fertilizer saving. In this case, average benefits of 148 and 44 € ha<sup>-1</sup> were realized when vetch and barley, respectively, were sown, while there was a reduction of 92 € ha<sup>-1</sup> when rapeseed was sown. The benefit probability distribution for each treatment and scenario is presented in Fig. 7.

Stochastic dominance is commonly used to rank alternatives or strategies that yield risky results. A strategy  $j$  exhibits first-order stochastic dominance over strategy  $k$ , with pdf of outcomes,  $\tilde{\pi}_j$  and  $\tilde{\pi}_k$  (measured in € ha<sup>-1</sup> in our case), defined by their cumulative distribution functions (CDFs),  $F_j(\pi)$  and  $F_k(\pi)$ , if  $F_j(\pi) < F_k(\pi)$  for all  $\pi$  (Hardaker et al., 1997). Four sets of CDFs (vetch, barley, rapeseed, and fallow) are represented for SN, LN, and LF in Fig. 7. Only in SN does vetch exhibit first-order stochastic dominance over barley, rapeseed, and fallow. In LN and LF, vetch stochastically dominates barley and fallow but not rapeseed. However, in LN and LF the CDF of vetch intersects with that of rapeseed in the highest values of the range of economic outcomes (more than 500 € ha<sup>-1</sup>).



**Fig. 6.** Probability distribution of the prices of maize grain (humidity 14%), fertilizer (ammonium nitrate, N 33.5%) and cover crop forage (barley and vetch, humidity 12%).

**Table 2**

Benefit distributions for the three scenarios studied: residue sold (SN), residue not sold and no fertilizer saving considered (LN), residue not sold but fertilizer saving considered (LF).

Treatment	SN	LN	LF
Residue	Sold	Left	Left
Fertilizer reduction	No	No	Yes
<i>Mean (€ ha<sup>-1</sup>)</i>			
Vetch	356	115	148
Barley	256	4	44
Rape seed	49	-118	-92
Fallow	12	12	12
<i>Median (€ ha<sup>-1</sup>)</i>			
Vetch	358	138	171
Barley	274	37	76
Rape seed	2	-168	-141
Fallow	20	20	20
<i>Percentile 25% (€ ha<sup>-1</sup>)</i>			
Vetch	46	-165	-133
Barley	-62	-297	-255
Rape seed	-343	-482	-461
Fallow	-235	-235	-235
<i>Percentile 75% (€ ha<sup>-1</sup>)</i>			
Vetch	653	399	433
Barley	581	313	356
Rape seed	407	299	255
Fallow	258	258	258

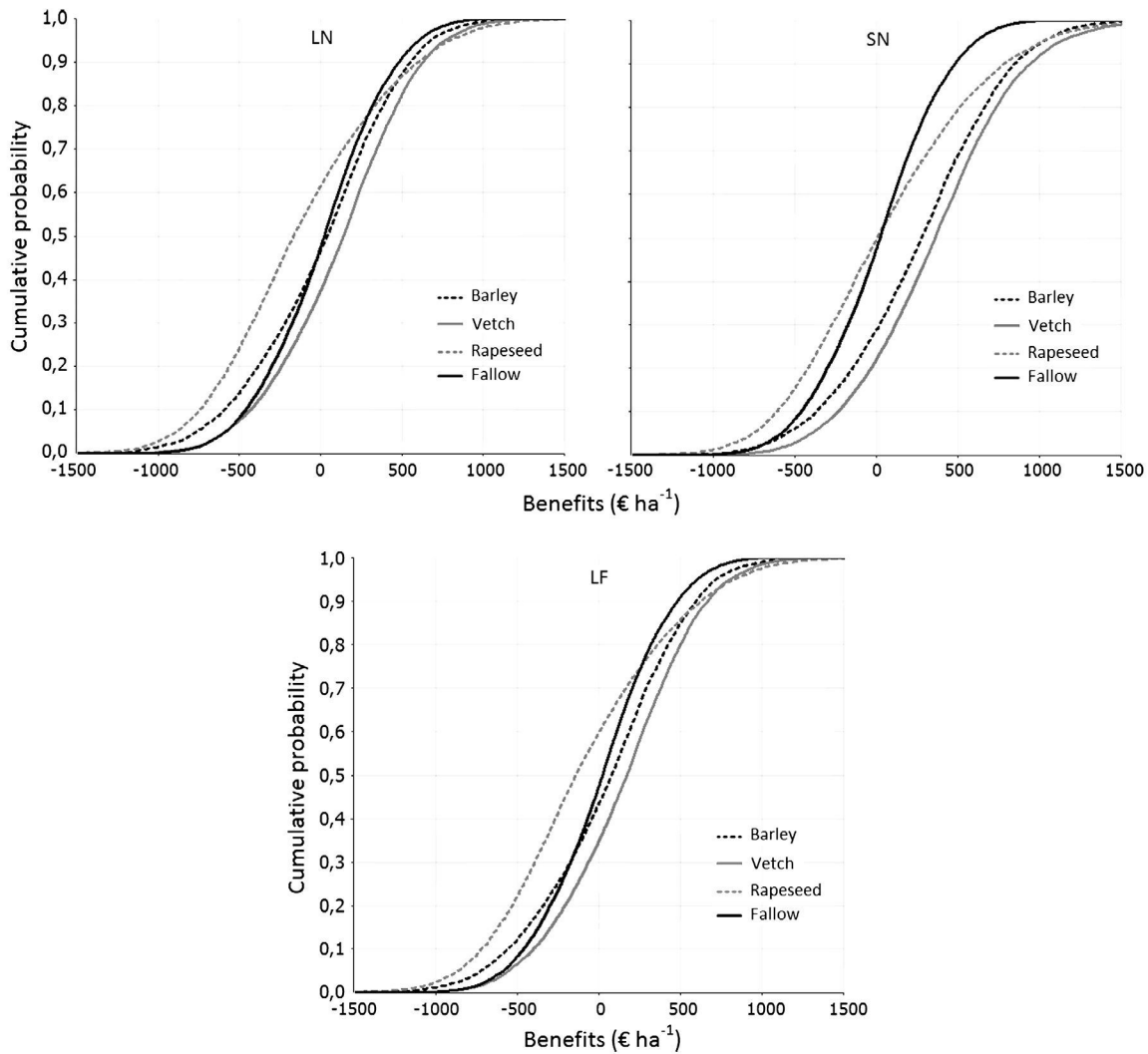
Note, however, that for very risk adverse farmers – more concerned with the left tail of benefit distribution – fallow is a better strategy than barley and rapeseed in the LN and LF scenarios.

CC benefit distributions presented a larger range of benefit variation than fallow (Fig. 7). Curve shapes were more horizontal, which corresponded with a larger difference between the 75% and 25% percentile values (Table 2), reaching 781 € ha<sup>-1</sup> for rapeseed treatment when residue was not sold and no fertilizer saving was considered, 610 € ha<sup>-1</sup> for barley, 564 € ha<sup>-1</sup> for vetch, and only 493 € ha<sup>-1</sup> for fallow. When residue was sold, shapes were similar, with the difference between the 75% and 25% percentile values reaching 750 € ha<sup>-1</sup> for rapeseed, 643 € ha<sup>-1</sup> for barley, and 607 € ha<sup>-1</sup> for vetch. Selling residue was the most profitable option in all CC treatments, followed by fertilizer saving. Only when rapeseed was grown did the introduction of CC reduce the benefits in more than 50% of years.

### 3.5. Effect of cover crop on nitrate leaching and economic benefit

Based only on the measured values analyzed in this second study (without Monte Carlo simulations), the use of barley as a CC greatly reduced nitrate leaching in comparison with the fallow (more than 100 kg N ha<sup>-1</sup> and year on average), but the economic results depended on the use of the CC biomass (Fig. 8). On the one hand, when barley residue was incorporated in the soil the benefit diminished with respect to the fallow (160 € lost per ha and per year on average), and therefore the alternative LN was located in quadrant III. On the other hand, if the barley biomass was sold as forage, the benefit was larger than in the fallow (177 € per ha and per year on average) and then the alternative SN was situated in quadrant IV.





**Fig. 7.** Benefits increase cumulative probability for the different treatments and scenarios: residue sold (SN), residue not sold and no fertilizer saving considered (LN), residue not sold but fertilizer saving considered (LF).

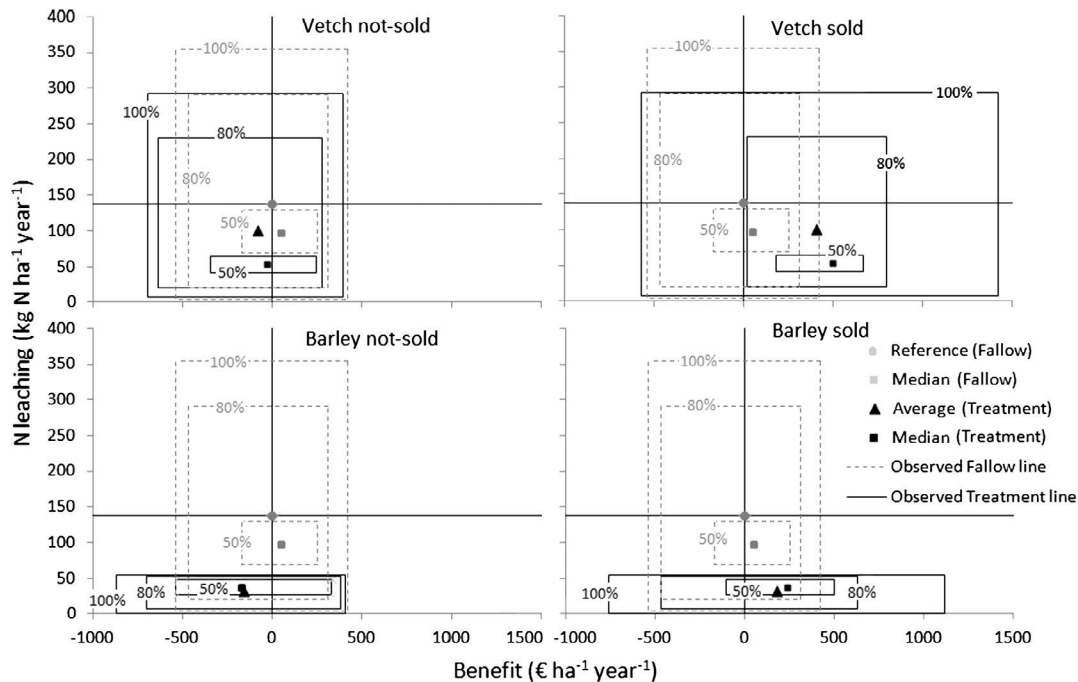
On average, nitrate leaching was reduced when the fallow was replaced by vetch (more than 60 kg N per ha and per year on average), but the economic results depended on the use of the CC biomass. When the vetch residue was incorporated in the field the benefit decreased with respect to the fallow (78 € lost per ha and per year on average), and therefore the alternative LN was located in quadrant III. If the vetch biomass was sold as forage, the benefit was larger than for the fallow and barley (407 € per ha and per year on average) and then the alternative SN fell clearly in quadrant IV. But years in which N accumulation after vetch was followed by heavy rain led to an increase in nitrate leaching (Gabriel et al., 2012); therefore, one out of four years in which the fallow was replaced by vetch was in quadrant II.

Variation in the prices of agricultural products did not change the quadrants where the scenarios were located, but did vary the benefit range (data not shown). With a theoretical increase of 33% in all costs and prices (maize and forage prices included), all CC management strategies presented a wider range between maximum and minimum benefit increase with respect to the fallow. With a theoretical decrease of 33% in all costs and prices, the economic risk was reduced leading to a narrower range of benefit increases.

#### 4. Discussion

Farmers need improved information about efficiency, quality, and quantity with regard to the effect of introducing a CC in the rotation. Environmental improvement has already been proved by several authors (Hargrove, 1991; McCracken et al., 1994; Salmérón et al., 2010; Quemada et al. 2013), but adoption of CC in dry regions has often been limited because of unsuccessful stand establishment or low water use efficiency (Unger and Vigil, 1998). Nevertheless, in irrigated semiarid areas where CC establishment can be assured, consequent soil or nutrient conservation could increase the sustainability of cropping systems. Moreover, replacing fallow with CC may enhance soil aggregate stability (Roberson et al., 1991) and water retention capacity (Quemada and Cabrera, 2002), two relevant factors in irrigated systems. But, in intensively fertilized systems, CC shows little or no benefit to subsequent crops, and in some cases it can reduce it (Tonitto et al., 2006). With all these possibilities an economic study may enhance the assessment of this strategy.

In our experiments, enough N was applied as a fertilizer to meet the requirements of maize, and replacing fallow with CC had little effect on maize yield (Gabriel and Quemada, 2011). However, there



**Fig. 8.** Economic benefit versus nitrate leaching observed during 4.5 years for the baseline and the different treatments and residue management (sold or no-sold as forage) scenarios. Rectangles delimited percentage of observed points (50% rectangle borders equivalent to percentiles 25% and 75%, and 80% to percentiles 10 and 90) for the fallow (dashed lines) and the treatments (solid lines). Actual prices used for maize 205, forage 102, and for barley, and vetch 214 € Mg<sup>-1</sup>.

were some tendencies that seemed to be augmented when the yield probability distribution was calculated for each treatment. In this case, the increase was larger than 850 kg ha<sup>-1</sup> on average with vetch treatment and larger than 300 kg ha<sup>-1</sup> with barley, but diminished by 200 kg ha<sup>-1</sup> with rapeseed. This result is in agreement with the results of studies done by Vyn et al. (1999), where non-legume CC increased corn yield. However, it stands in contrast with the results of Thorup-Kristensen (1994), who reported a yield reduction after non-legume CC. The yield increase after vetch is consistent with most results reported in the literature as summarized in a meta-analysis conducted by Miguez and Bolle-ro (2005).

The pdf combined with Monte Carlo simulation was a meaningful quantitative tool for evaluating the economic impact of various alternative strategies. In our case, pdfs for the studied variables were based on field observed results from 4.5 years, where climatic conditions were very different and captured the high interannual variability of Mediterranean weather (Gabriel and Quemada, 2011; Gabriel et al., 2012). However, to increase results reliability it would be convenient to extend this methodology to larger time series and different locations.

Introducing a CC involved extra costs with respect to fallow as the initial investment, because new seed, herbicide, extra field operations, and sometimes new equipment were necessary. Additional costs varied from 28 to 73 € ha<sup>-1</sup> but, in this case, even without selling the CC residue and without a fertilizer reduction, the vetch treatment increased the benefits with respect to the fallow in almost two out of three years and the barley treatment in one year out of two. However, this increase could have been smaller if maintenance operations to keep the fallow free of weeds had been taken into account. Also, the extra cost of contact herbicide in CC treatments could have been substituted by increased gasoil consumption if plowing had been used to kill the CC, a very common technique when direct sowing is not used. When residue was sold, the net benefit increased in the CC and there were more benefits than in the fallow in close to 80% of the years with the vetch treatment and 70% with the barley treatment.

There is another profit source of CC in the form of fertilizer saving when residues are left in the field (Snapp et al., 2005). In our work the fraction of N in the CC available for the next maize crop (N<sub>f</sub>) was over 0.65, estimated based on plant N uptake and soil N<sub>min</sub> content differences between CC and fallow treatments. These values are high, but include the N effect of the above- and below-ground biomass and are expressed only as a fraction of the above-ground biomass. Other authors, like Andraski and Bundy (2005) and Decker et al. (1994), observed similar N<sub>f</sub> for various CC in the USA. They showed that growing maize after CC reduced N fertilization needs from 0 to 67 kg N ha<sup>-1</sup> depending on CC biomass production and species. If the residue is sold, the fertilizer reduction will be smaller because only the N from root mineralization will return to the soil. Specific experiments for a better quantification of the effect of CC on fertilizer savings are needed.

The decision between selling the CC biomass as animal feeding or incorporating the residue as a green manure was analysed by plotting the total nitrate leaching versus the economic benefit. With the prices considered, selling the CC as animal feeding generated larger benefits than fertilizer savings. With barley and vetch treatments, selling the forage made the difference between being in quadrant III or IV. In quadrant III the economic benefit decreased, and alternatives would be feasible if subsidies to compensate for the economic losses were granted. Subsidies could be justified based on the agroenvironmental services provided by leaving the CC residue in the field, but most of the benefit would accrue to the farmer, contributing little or nothing to the public good dimension. In quadrant IV, the nitrate leaching was reduced and the economic benefit increased; therefore, there is no need for subsidies provided there is a market for the forage. Treatment combination and prices variations are multiple, so this representation provides an easy way to compare different scenarios and strategies. In our case, variation in the price of agricultural products (±33%) did not affect the quadrant distribution of the scenarios, but showed that raising the prices increases the differences between treatments and the risks between years.



## 5. Conclusions

Replacing the fallow period with CC in an irrigated maize system had an effect on maize yield and CC biomass production that varied greatly depending on the year and the CC species. Therefore, uncertainty analysis using Monte-Carlo stochastic simulation models provided meaningful quantitative tools for evaluating the economic impact of various alternative strategies. The log-logistic with a minimum of zero was the probability distribution function that better adjusted to the CC biomass production observed during the 5 years of study, while the triangular distribution was the pdf that better adjusted to the CC effect on subsequent maize yield. Mean biomass production was 3004 kg ha<sup>-1</sup> for barley, being larger than 2154 kg ha<sup>-1</sup> in 50% of years; 1928 kg ha<sup>-1</sup> for vetch, being larger than 1011 kg ha<sup>-1</sup> in 50% of years; and 2428 kg ha<sup>-1</sup> for rapeseed, being larger than 1298 kg ha<sup>-1</sup> in 50% of years. When vetch and barley were grown as CC, maize yield tended to increase (850 kg ha<sup>-1</sup> and 300 kg ha<sup>-1</sup> respectively, on average); whereas rapeseed tended to decrease maize yield. These results suggest that CC increases crop yields, being a strategy that stochastically dominates the fallow.

Combinations of CC management practices gave three alternative scenarios that were compared to the baseline, namely, fallow followed by a maize crop. Introducing a CC entails extra costs with respect to the fallow, because of the requirements for new seed, herbicide, and extra field operations. Taking into account these costs and without selling the CC biomass or considering a fertilizer reduction, vetch treatment increased benefits with respect to the fallow in almost two out of three years. When the vetch biomass was sold as forage, benefits increase in more than 80% of the years with respect to the fallow. Barley was beneficial in only 50% of the years when the residue was not sold or fertilizer was not reduced, and in 70% of the years when it was sold as forage. Overall, when the product prices were considered, selling the CC as animal feed generated more economic benefits than fertilizer savings.

Plotting nitrate leaching during each CC/maize cycle against the economic benefit allowed the baseline and alternative scenarios to be compared. There was a slight reduction in economic benefit when the vetch residue was left in the field, but a large benefit resulted when the vetch was sold as forage with respect to the fallow. However, even if replacing the fallow with vetch reduced nitrate leaching on average, in one out of four years it led to an increase in nitrate leaching. Barley always reduced nitrate leaching with respect to the fallow, but the economic benefit was only larger than in the maize/fallow when the forage was sold. Therefore, if agroenvironmental services provided by leaving the barley residue in the field were to be promoted, farmer subsidies would be required to encourage cover cropping.

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